

The Variable Radioisotope Heater Unit for the Cassini Spacecraft

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ABSTRACT

This paper describes the Variable Radioisotope Heater Unit; its development, performance, and effectiveness at controlling the temperatures for the Cassini spacecraft thruster clusters.

To explore the Saturn system, the Cassini spacecraft relies on the electrical power from three Radioisotope Thermoelectric Generators, but the large power demand for science and engineering functions severely limits the electrical power available for temperature control purposes. The Variable Radioisotope Heater Unit combines the heating- and temperature-control functions into one nonelectrical self-controlled unit, thereby freeing up electrical heater power for other uses on the spacecraft.

INTRODUCTION

CASSINI MISSION OVERVIEW-Cassini will be launched on a Titan IV/Centaur in the October 1997 launch window [1]. The first burn of the Centaur upper stage places Cassini into a low-Earth orbit and the second burn injects the spacecraft (S/C) into the first leg of a trajectory (Figure 1) that depends on gravity assist flybys of Venus (twice), Earth and Jupiter to intercept Saturn in 2004. The last gravity assist at Jupiter increases the S/C velocity (relative to the Sun) from 11.6 to 13.6 km/sec. After almost a seven-year flight, one of the two 400-N liquid rocket engines, firing for 88 min, inserts the S/C into orbit about Saturn. The orbiter will be active for up to four years exploring Saturn, its rings, and its numerous moons. More than thirty flybys of the moon Titan are planned and on one of the early encounters a probe will be launched into the Titan atmosphere.

An international team consisting of approximately 1300 people in 16 European countries and 3000 people in 32 states in the U.S. is involved in various aspects of the Cassini mission, including design, fabrication, and planning [1]. The Titan probe, named Huygens after the Dutch scientist who discovered Titan and the Saturn rings, is being developed by the European Space Agency. Both the mission and the S/C bear the name of the French-Italian astronomer, Jean Dominique Cassini, who discovered several of the moons of Saturn and the gap in Saturn's main rings. The High-Gain Antenna (HGA) is provided by the Italian Space Agency. There are European experiments on the

orbiter and U.S. experiments on the probe. The orbiter is being assembled by the Jet Propulsion Laboratory (JPL) which will also manage the Cassini mission for the National Aeronautics and Space Administration.

Cassini's trajectory will result in a solar environment which exposes the S/C to 2.7 suns (perihelion, 0.61 AU) and 0.01 suns (Saturn, 10 AU). And, the pass through the shadow of Saturn can last as long as 18 hours. Although the S/C is 3-axis stabilized and Sun-oriented, there are many off-Sun maneuvers for trajectory corrections and/or communication purposes. These maneuvers are time-constrained until the S/C is beyond 5 AU. Inside of 5 AU, all the maneuvers are performed so that full advantage can be taken of the shading provided by the 2.7-m diameter probe. While the 4-m diameter HGA is Sun oriented, it shades the S/C.

CASSINI SPACECRAFT CONFIGURATION - Two views of the mechanical configuration (without thermal blankets) are shown in Figure 2. In addition to the science complement on the Huygens probe, there are twelve science subsystems that will remain with the orbiter. Mounted on the Remote Sensing Pallet

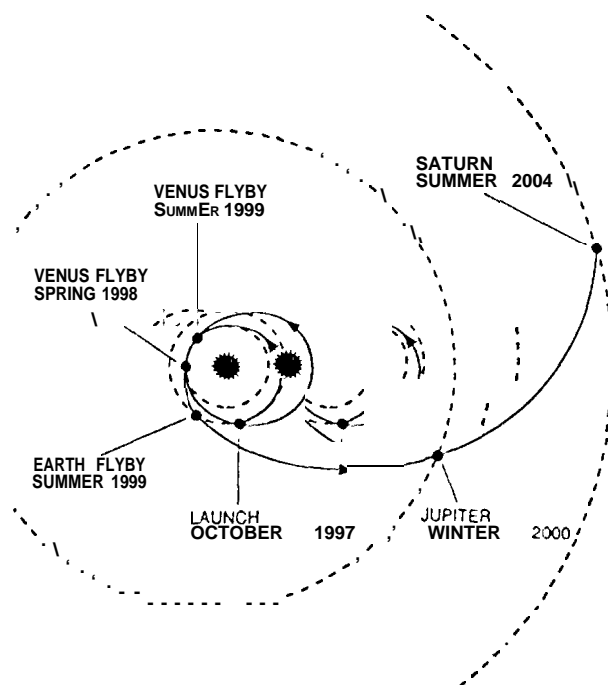


Figure 1. Cassini Trajectory to Saturn.

are the primary and backup Stellar Reference Units (star trackers), the Visual and Infrared Mapping Spectrometer, the wide- and narrow-angle cameras of the Imaging Science Subsystem, and the Composite Infrared Spectrometer. Two magnetometers are mounted on the Magnetometer Room Assembly which, for thermal protection, will be deployed after the second Venus flyby and after reaching 0.55 AU. The Ion and Neutral Mass Spectrometer, Plasma Spectrometer, and part of the Magnetospheric Imaging Instrument mount off of the Fields and Particles Pallet. A Langmuir Probe, Radar, and an HGA (Radio Science) are mounted off of the Bus. Supported off of the Upper Equipment Module are the other part of the Magnetospheric Imaging Instrument (the Ion and Neutral Camera sensor), the Radio and Plasma Wave Science and the Cosmic Dust Analyzer.

The Propulsion Module (Figure 3) is the mechanical core of the S/C. The Upper Equipment Module with the mated Bus and the Lower Equipment Module are attached to this central structure. Buildup of the configuration continues with the addition of the Reaction Wheel Activators, the Inertial Reference Unit, Probe Support Avionics, HGA, etc. The Huygens probe and Radioisotope Thermoelectric Generators (RTGs) will be installed at the Kennedy Space Center after the S/C has been fully blanketed.

Except for radiators, louvers, instrument apertures, the generators, and the HGA, the S/C is completely enclosed with multi-layer insulation (MI) thermal blankets. Figure 2 depicts the S/C without the blankets. At first glance, the finished S/C will appear gold except for the large white HGA. Closer inspection will reveal numerous black apertures, metallic louvers, and several white radiators. The gold appearance results from the

outer layer of the thermal blankets, which is aluminized Kapton with the Kapton facing out and coated with iridium tin oxide. The thermal blankets reduce the heat loss from the S/C, minimize electrostatic discharge (iridium-tin-oxide coating), reflect the Sun (second-surface mirror) during maneuvers, and provide an effective breakup surface for micrometeoroids.

THRUSTER CLUSTER THERMAL DESIGN - Attitude control is provided by four thruster clusters, each of which contains four 0.9-N hydrazine thrusters (Figure 4). To maximize turning torque, three struts suspend a boxlike cluster from the central structure. MI blankets minimize the heat loss from the cluster housing, which is thermally coupled radiatively to the central body by the blanketed but open boom cavity. Heat from the RTG waste-heat system is instrumental in establishing the propulsion module central body as a stable temperature sink [2]. The cluster sides facing the short (0.5-m) boom cavity are painted black, and the inside surface of the boom cavity is the aluminized side of the MI thermal blanket which enhances the radiation coupling to the central body sink. For long thruster firings, this coupling helps to limit the warm-up of the cluster housing. Opening the boom cavity to the central body and cluster housing eliminated the need for electrical heaters for the propellant lines going to the clusters.

Heat loss from the four thrusters dominates the cluster energy balance when the thrusters are not firing, and the coupling to the central body is not sufficient to maintain a required temperature. Since the initial thermal design utilized electrical heaters, additional heat to the cluster housing is required. The electrical heaters could be commanded off which is beneficial for the long thruster firings. However, the S/C electrical power

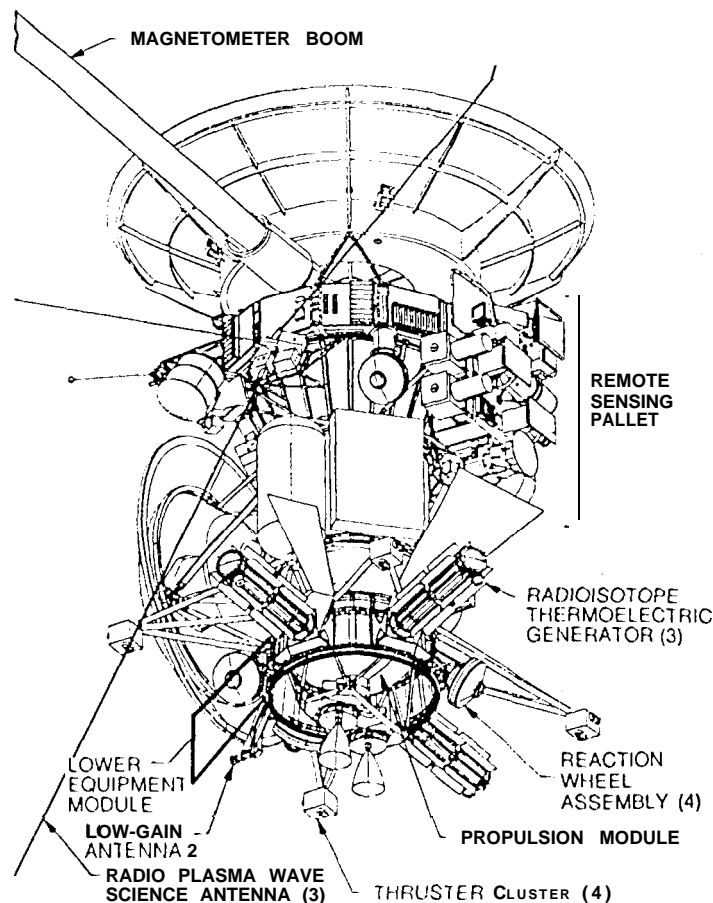
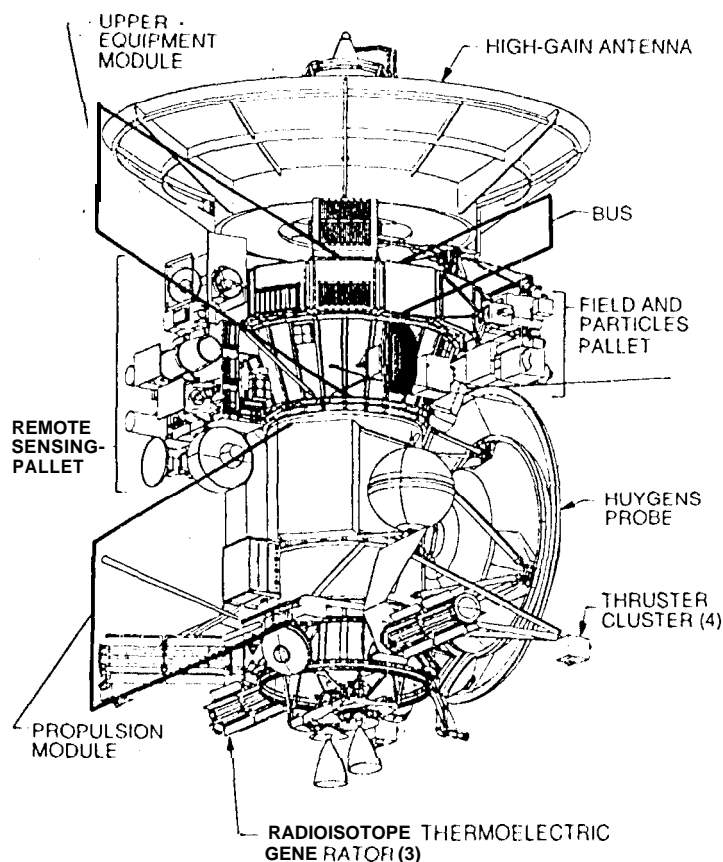


Figure 2. Cassini Spacecraft,

crunch forces the cluster thermal design to rely more on the use of Radioisotope Heater Units (RHUs), which cannot be turned off, and less on electrical power. The Variable Radioisotope Heater Unit (VRHU) was developed to eliminate the need for electrical heater power and automatically reduce the heat supplied to the cluster housing during thruster firings.

VRHU CONCEPT - The VRHU combines the heating- and temperature-control functions into one nonelectrical self-controlled unit. It consists of a cylindrical RHU holder that contains up to three RHUs and rotates on bearings when driven by two temperature-sensitive bimetallic springs. As illustrated in

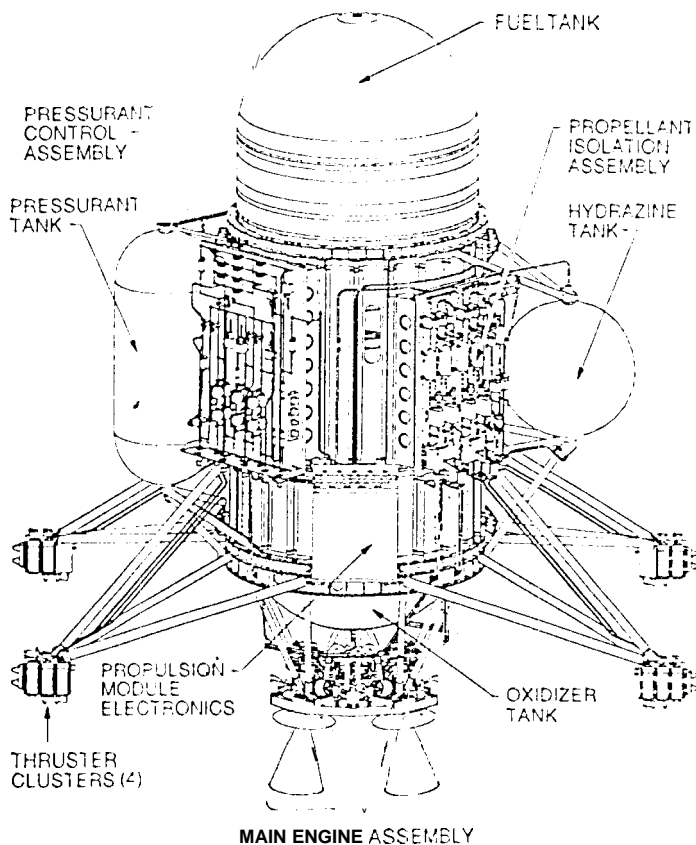


Figure 3. The Cassini Propulsion Module.

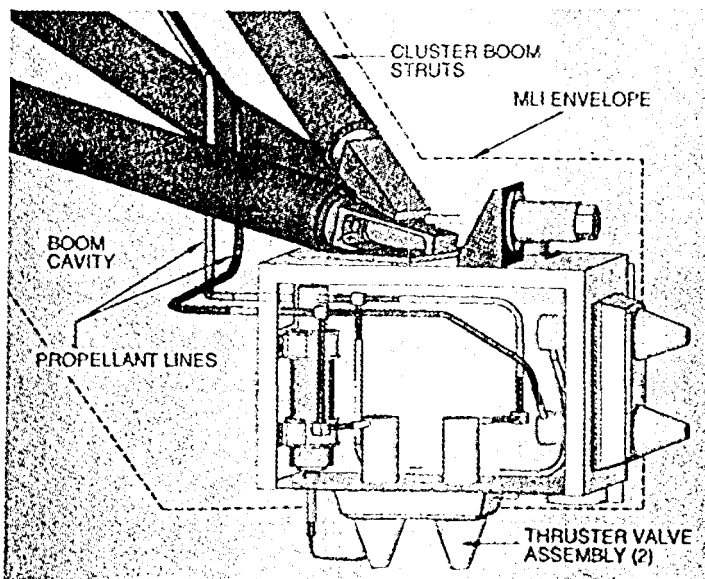


Figure 4. Thruster Cluster Boom Assembly.

Figure 5, half of the RHU holder is painted white while the other half is covered with a twenty-two layer MLI blanket. The RHU holder is thermally isolated from the bimetal actuator, which is thermally coupled to the hardware that is being temperature controlled. When the hardware (cluster housing) temperature goes below the set-point temperature for the bimetallic springs, the holder is rotated so that the high-emittance surface (white paint) faces the hardware (heat in) and the low-emittance side (blanketed) faces space (fully closed position). When the hardware temperature goes above the set point, the holder rotates to expose the high-emittance side to space (heat out) and exposes the hardware to the blanketed portion of the holder (fully open position). The bimetallic springs can be calibrated for a desired open-point temperature between -20 and 50°C and the fully open position will occur 28°C above the open-point temperature.

At the center of the RHU is a plutonium dioxide ceramic fuel pellet. A single RHU weighs 42 g and will fit snugly in a cylindrical enclosure 26 mm in diameter and 32 mm long. By means of radioactive decay of its plutonium fuel, each unit delivers $1.04 \pm 0.03\text{ W}$ at encapsulation. The time of decay is illustrated in Figure 6 for the Cassini primary and backup missions. Up to 40 and 60 RHUs will be used on the Huygens probe and orbiter, respectively. The Galileo S/C, currently en route to Jupiter, utilizes 120 RHUs.

Because of the high temperatures, an all-Kapton MLI blanket is used on the holder. The exterior layer is second-surface aluminized Kapton to reduce the solar loading during the off-Sun maneuvers. The interior layers are constructed of embossed aluminized Kapton.

Figure 7 shows the VRHU in the half-open position. Without RHUs, the unit weighs 390 g . Each cluster thermal design requires four VRHUs but has provisions for five, as illustrated in Figure 8. Although the 3-RHU unit fits nicely on the cluster housing, the number of VRHUs was driven by the Cassini project

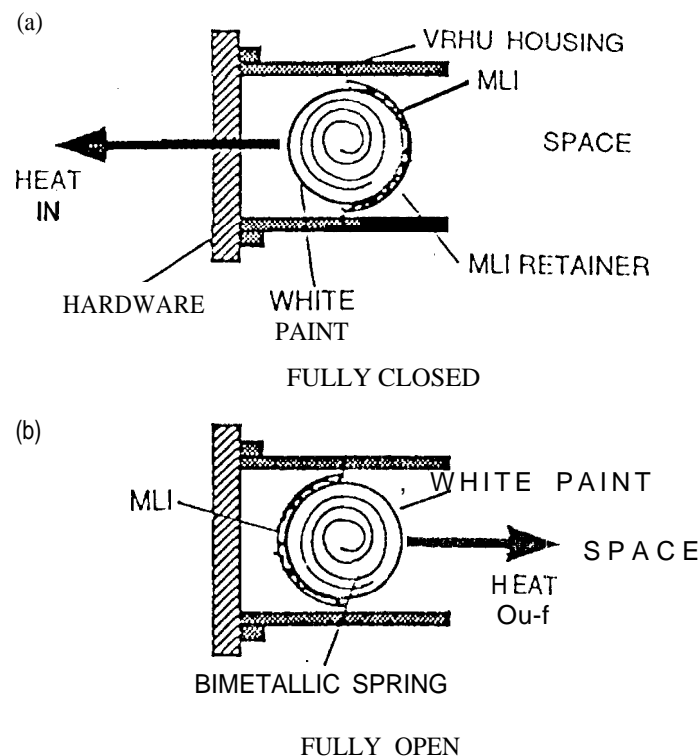


Figure 5. The Variable Radioisotope Heater Unit Concept.

requirement that acceptable temperatures be maintained with one VRHU failed open or closed. Each VRHU holds up to 3RHUs. When only twoRHUs are used, a spacer replaces the thirdRHU in the 2-RHU configuration. Both a 2- and a 3-RHU VRHU have been characterized.

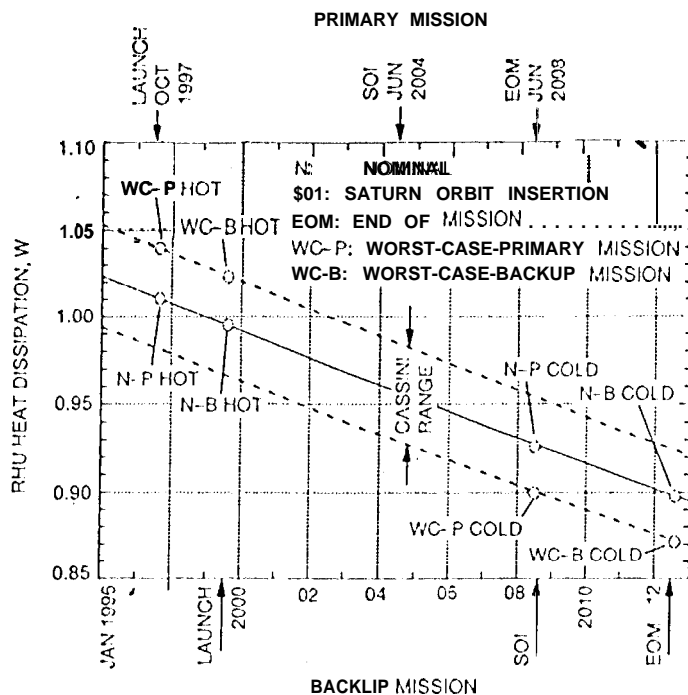


Figure 6. RHU Heat Dissipation for the Cassini Mission.

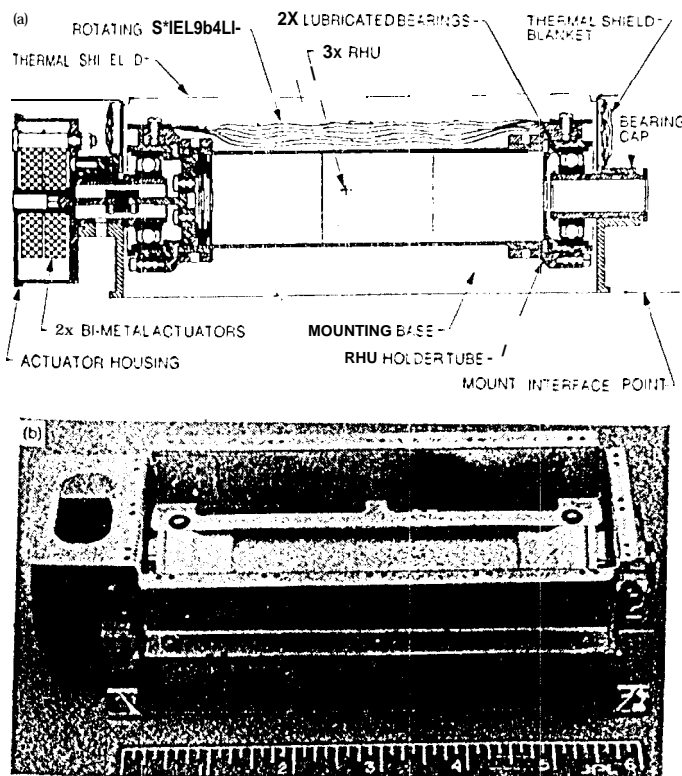


Figure 7. The Variable Radioisotope Heater Unit.

DISCUSSION

TEMPERATURE AND HEATER REQUIREMENTS - Requirements have evolved during the development of the VRHU. The mounting-surface temperature must not exceed the set-to-open and/or fully open temperature range by 60°C or the bimetallic springs could be damaged. The RHU holder should not exceed 285°C to assure an RHU temperature of less than 300°C.

Because of its cost, [he RHU must be efficient, since any additional heat only comes in 1-W (an RHU) increments. An efficiency of better than 80% (heat into [he hardware ÷ RHU heat output x 100%) was imposed.

For the Cassini Thruster Cluster application, [he Thruster Cluster housing allowable flight temperature requirement is 20 to 50°C. The set-to-open temperature for each VRHU has been chosen as 25 ± 3°C.

VRHU 1 THERMAL DEVELOPMENT TEST - The Thermal Development test, performed at JPL in August/September, 1993, was divided into four phases: Phase 1, Bimetallic Spring Characterization: Verify the VRHU calibration in the test setup; Phase 2, Mounting Plate Calibration: Calibrate the heat input to the mounting plate without a functioning VRHU; Phase 3, Nominal Flight: Characterize the VRHU performance in simulated nominal flightlike conditions; and Phase 4, Sun Simulation: Characterize the VRHU performance during direct Sun illumination.

Test Article - The test article consists of a 3-unit VRHU engineering model hard-mounted to a 30.5-x20.3-x0.3-cm aluminum plate, representative of a mounting surface. Figure 9 shows the test article instrumented without the mounting-plate blanket.

The back of the mounting plate was painted black for better test control of the plate temperature. The front (where the VRHU was mounted) was left unfinished, except for the two areas, shown in Figure 10, that were black-anodized to increase the coupling between the mounting plate and the bimetallic housing and also the coupling between the mounting plate and the RHU

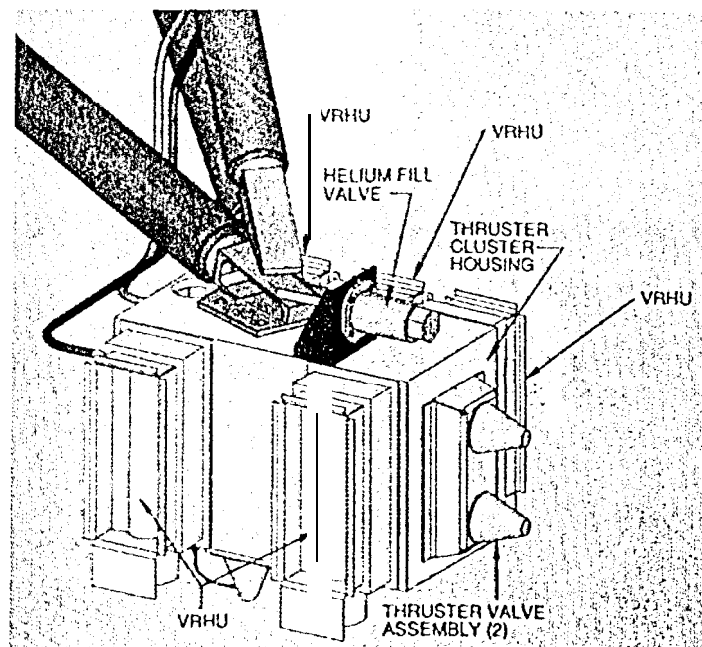


Figure 8. Thruster Cluster with VRHUs.

holder (black anodize is a possible finish for the flight Thruster Cluster housing). An airplane instrument panel vibrator was mounted on the back of the plate and was used in case the VRHU got stuck.

Test Setup- The test article was placed in a 0.91-m thermal vacuum chamber. Shroud dimensions and the test setup are shown in Figure 11. This chamber was equipped with a 0.46-m diameter quartz window and a liquid nitrogen-cooled shroud, including a door shroud. The test article was suspended from the chamber by stainless steel wires (#2 gauge). To decrease the warm chamber window effects on the test results, the test article was located as far as possible from the window and the view of the window was decreased by using an MLI blanket with a small view port. A view port was necessary for observation during most of the test to confirm the opening position. A full window was used during Phase 4 (solar simulation).

A Spectrolab Mark III X25 was used to simulate the Sun. This system provided a beam size that was sufficient to illuminate the entire test article and can produce up to three solar constants. The solar source was calibrated before the beginning of Phase 4 and a Kendal radiometer was collocated with the test article. A total of 24 thermocouples were used in the test, and three of them can be seen in Figure 9. An electrical simulator was used in place of the RHUs.

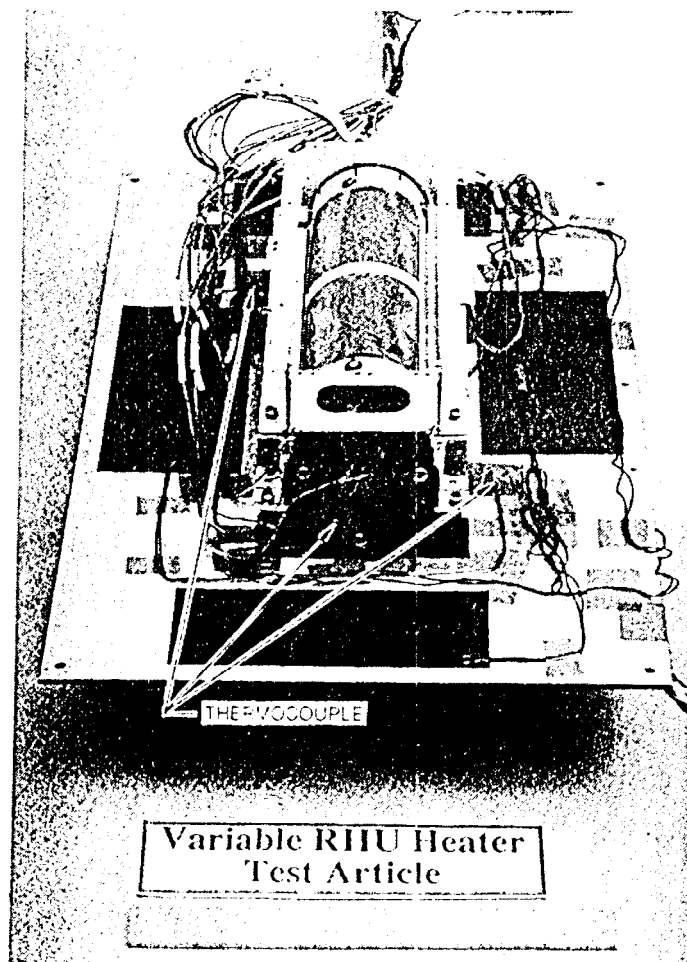


Figure 9. VRHU Test Hardware.

RESULTS OF THE VRHU TEST

TEST PHASE 1 - Phase 1 was used to verify the rotation as a function of the bimetallic springs' housing temperature for

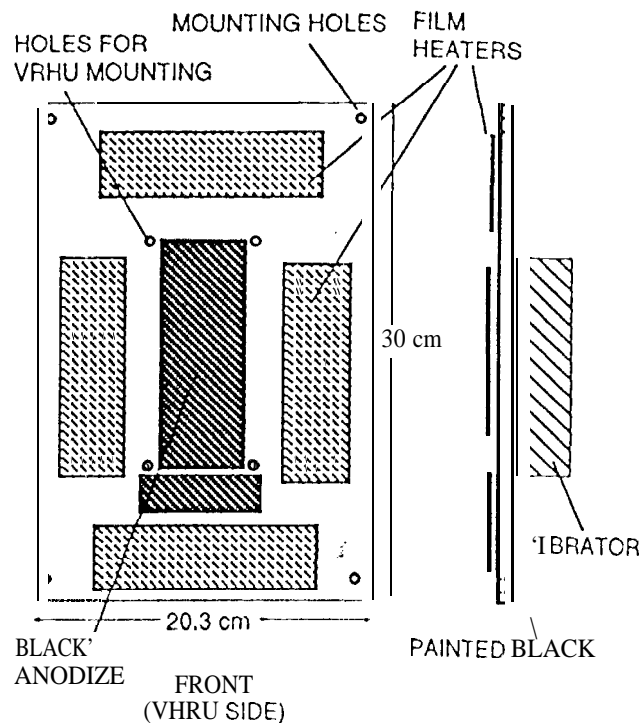
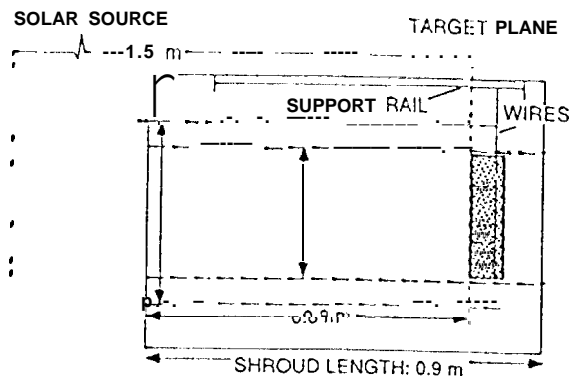


Figure 10. VRHU Test Plate.

SIDE VIEW



FRONT VIEW

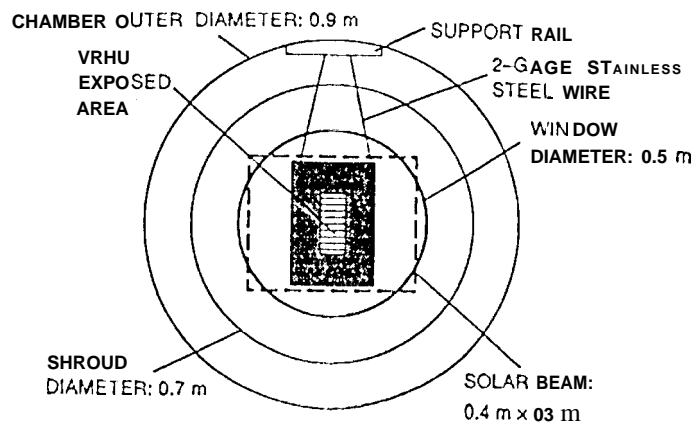


Figure 11. VRHU Chamber Configuration.

the test configuration. This test and the subsequent in-air test showed that the instrumentation cable (four 26-gauge RHU heater simulator wires and two 30-gauge thermocouple wires) coming from the RHU holder increased the 28°C delta temperature to fully open by 11°C (to 39°C). Without the instrumentation cable, the rotation was as predicted.

For flight there are no instrumentation leads and for future cluster testing, only two leads for the RHU simulator are required. The VRHU thermal performance was characterized for the test rotational performance and has been corrected for the flight conditions.

TEST PHASE 2 - Phase 2 characterized the amount of heater power required to maintain the mounting-plate temperature (steady-state) over the test temperature ranges without heat from the VRHU. During this phase, the VRHU was blanketed and no power was delivered to the RHU simulators. The reduction in the plate heater power when the RHU simulators are on is a direct measurement of the VRHU performance at that temperature and opening angle.

TEST PHASE 3 - The thermal performance of the VRHU was characterized in Phase 3. The results showed that only 1.9 W of the 3 W (63% efficiency) were going into the hardware (fully closed and 10°C). Heat loss out of the instrumentation cable (from the VRHU holder) was measured at 0.26 W and would not be a loss for the flight configuration, "This additional heat would improve the efficiency to 73%.

Two sets of changes were made to the thermal blanketing to further improve the VRHU performance. Figure 12 illustrates the changes to the holder blanket and Figure 13 shows the changes to the mounting plate blanket (representative of the Thruster Cluster blanket). Initially all 22 layers of the RHU holder blanket were squeezed locally at the ends between the blanket retainer and the RHU holder. After the changes, only the outer two layers remained and one additional layer of glass tape was added locally at each screw to further improve the local thermal isolation.

The second blanket change reduced the VRHU exposed area by -19%. This change reduced the heat loss at the fully closed position but also reduced the heat rejection at the fully open position. The measured improvement in VRHU performance for both blanket changes (final blanket) is shown in Figure 14. With the final blanket configuration, the efficiency is 88% at the cost of a heat input of 0.7 W in the fully open position.

As previously discussed, the instrumentation cable from the holder required higher hardware temperatures to get the desired opening angle. Therefore, it is necessary to adjust the test curve (Figure 14) for the flight configuration (no cabling). For a constant rotation angle (Θ) it is only necessary to find $[\partial Q/\partial T]_{\Theta}$ to adjust the test performance.

From the test results for a fully closed VRHU ($\Theta = 0^{\circ}$):

$$\begin{aligned} [\partial Q/\partial T]_{\Theta=0^{\circ}} &= (Q_{@10^{\circ}\text{C}} - Q_{@26^{\circ}\text{C}})/(26^{\circ}\text{C} - 10^{\circ}\text{C}) \\ &= (2.37 - 2.28)/16 = 0.0055 \text{ W/}^{\circ}\text{C}, \end{aligned}$$

and for a fully open VRHU ($\Theta = 180^{\circ}$):

$$\begin{aligned} [\partial Q/\partial T]_{\Theta=180^{\circ}} &= (Q_{@64^{\circ}\text{C}} - Q_{@72^{\circ}\text{C}})/(72^{\circ}\text{C} - 64^{\circ}\text{C}) \\ &= (0.40 - 0.45)/8 = 0.0065 \text{ W/}^{\circ}\text{C} \end{aligned}$$

Based on the above, it was assumed that for the entire curve that $[\partial Q/\partial T]_{\Theta} = 0.006 \text{ W/}^{\circ}\text{C}$.

Since there was no significant deviation in the calibration for rotation angles less than or equal to 45° only the data above the 45° rotation were adjusted. Results are shown in Figure 15 for [be 3-W anti ?-W configurations.

Since the RHU dissipation decreases with time (Figure 6) the predicted impact on the VRHU flight performance is shown in Figure 16.

The upper curve represents the maximum VRHU performance for the primary trajectory at the beginning of the mission (1997) and assumes that all 3 RHUs have a maximum heat dissipation (worst-case hot). The bottom curve is for minimum RHU heat dissipation at the end of the mission (2012) for the backup trajectory (worst-case cold). These performance curves are for worst case thermal design analyses. Actual VRHU performance, when the VRHU is loaded with all maximum or all minimum dissipating RHUs, decreases 8 and 10% over the course of the primary (11 years) and backup (13 years) missions, respectively.

TEST PHASE 4 - The location of the VRHUs on the Thruster Cluster is such that for S/C maneuvers the Sun is parallel to the plane of the VRHU opening until the S/C is beyond 5 AU. Since mission plans and/or configuration can change, the VRHU performance was evaluated for the Sun normal to the opening

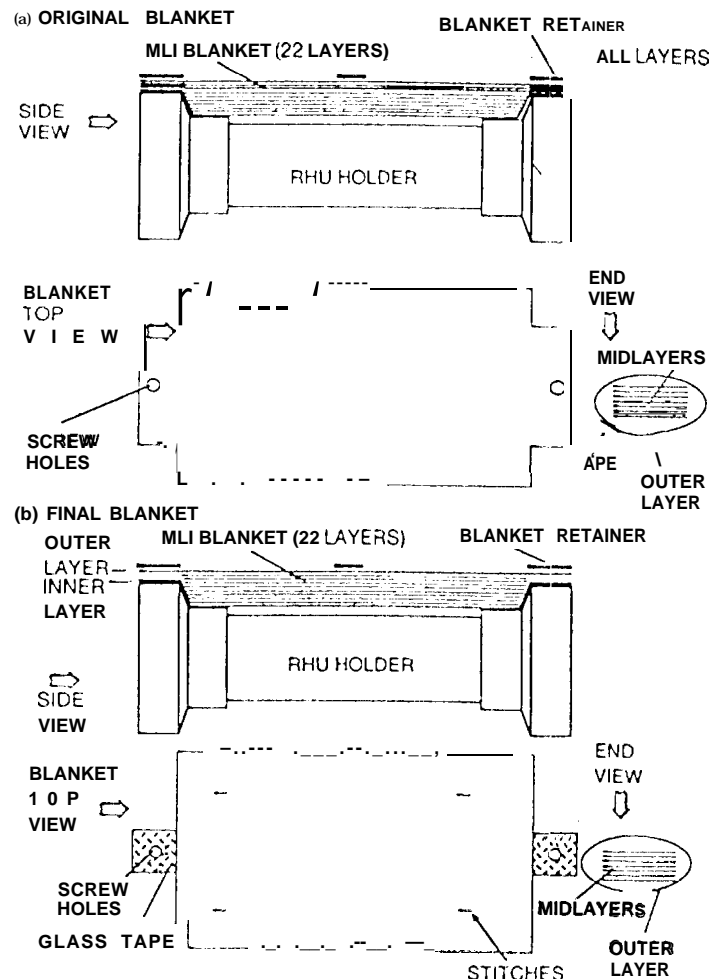


Figure 12. VRHU Holder Blanket Configuration Change.

(worst case). These steady-state results are summarized in Table 1, which also shows the temperatures for the VRHU with and without the Sun.

The solar loading increases with mounting plate temperature. This results because as the opening angle increases (due to increasing temperature) more of the higher solar reflective white paint is exposed. This change in properties coupled with the cavity effect, created by decreasing the blanket opening, results in more energy being reflected through the gaps along the RHU holder and onto the thermal shield where some of this energy is absorbed and conducted to the mounting plate by way of the aluminum mounting base. The solar loading is large and may be significant, depending on the application, if allowed to go to steady-state. It is not significant for the Cassini Thruster Cluster application. It can be reduced by lessening the cavity effect and changing the thermal shield height. These changes would drive the efficiency down, but 50% should still be realized.

These solar tests also confirmed that the temperatures of the VRHU remain very acceptable in this worst-case environment. The RHU holder is significantly below the 285°C limit and there are no material concerns (expansion effects, etc.) with the other temperatures.

CLUSTER PREDICTED PERFORMANCE - Table 2 illustrates the predicted temperatures for the Thruster Cluster Housing for the 4-VRHU configuration using 10 RHUs. Temperatures are within the requirements except for the steady-

state firing conditions in the Sun at perihelion. This is not a real condition since the maximum time in the Sun would be 30 min and the maximum firing time for the thrusters would be less than 15 min. A transient analysis of a 30-min maneuver, with solar and thruster firing continuously, shows the housing peaking at

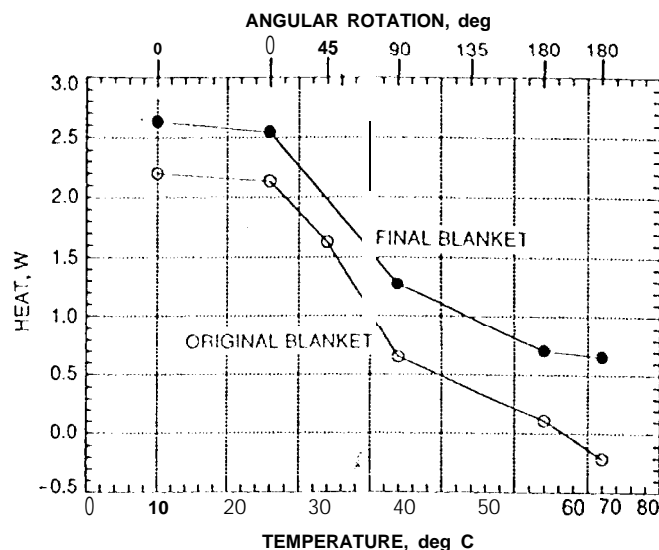


Figure 14. VRHU Test Characterization.

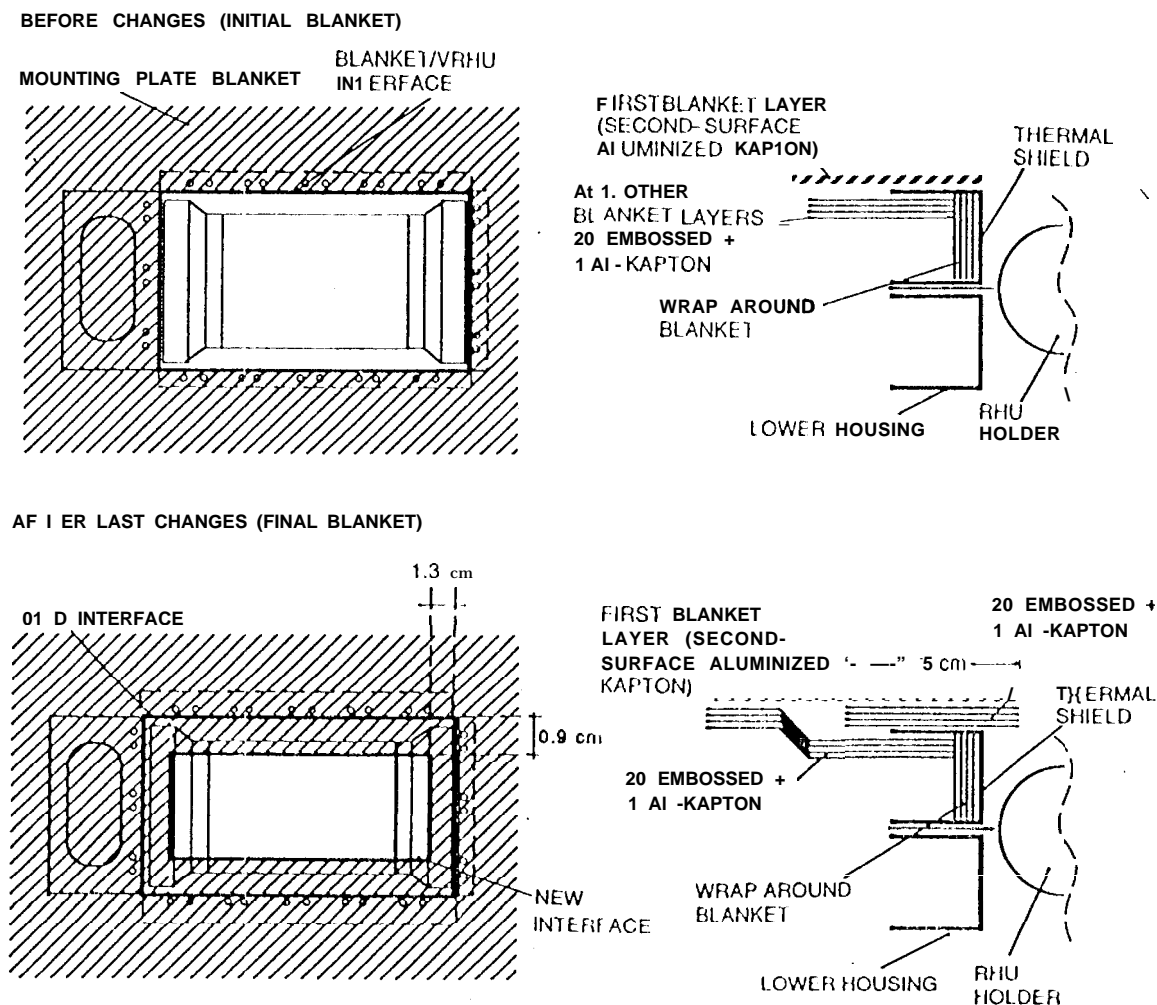


Figure 13. VRHU Hardware interface Blanket Change.

45°C, which gives adequate margin relative to the 50°C limit for this worst-case scenario. Without the solar loading (Saturn operations), continuous thruster firing is possible without exceeding the housing limit.

The thruster cluster thermal design will be tested with the VRHUs at the cluster thermal vacuum assembly test and with the Cassini S/C at the thermal vacuum systems-level test,

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The VRHU has been fully developed for the Cassini Thruster Cluster Application. Because of the costs of an RHU (\$31 K), a VRHU with 3 RHUs costs \$108 K or \$41 K/W. This compares to \$187 K/W for an electrical watt supplied by an RTG for Cassini. Therefore, it is a bargain for deep space exploration, but obviously it cannot compete with electrical heaters for S/C powered by solar panels.

The VRHU can be used with higher sink temperatures provided that the volume of the sink is relatively large. One

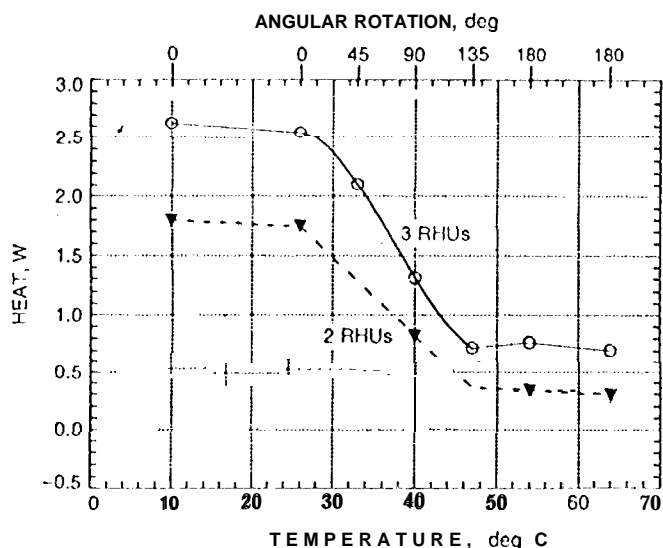


Figure 15. VRHU Flight Characterization.

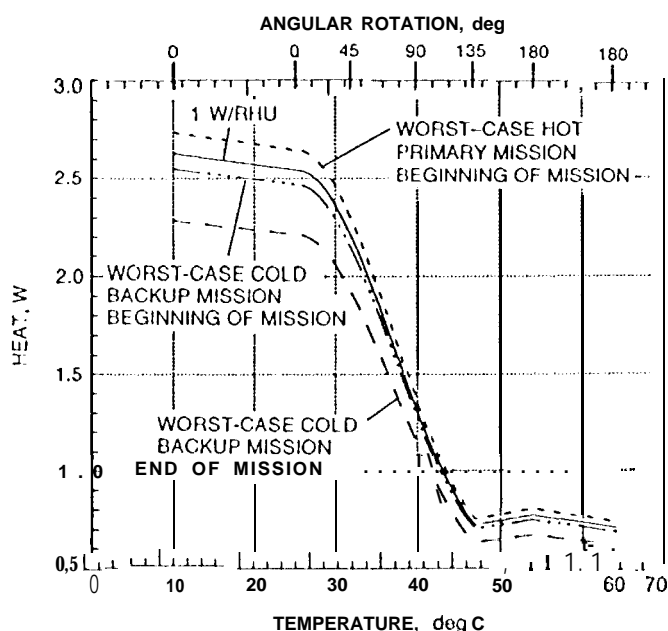


Figure 16. VRHU Cassini Mission Characterization.

application considered for Cassini is heating of the Pressurant Control Assembly. In this application, the VRHUs would be set to open at 35°C and to reject the heat into the Propulsion Module cavity. The RHU holder would run warmer to compensate for the higher temperature sink. Some modification of the thermal shield would be necessary. The Pressurant Control Assembly blanket interface with the VRHU would be different than that interface for the cluster. With these changes, analyses indicate that the VRHU performance would be approximately the same as for the cluster application.

In conclusion, the VRHU developed for the Cassini S/C represents a flexible automatic temperature control device that should prove to be another useful thermal design tool for the S/C thermal engineer.

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Table 1. VRHU Temperatures and Performance With and Without Solar Illumination

Item	Solar Irradiance, Suns					
	1.0	1.0	0	2.7	2.7	0
Performance (watts)						
Total input	4.14	4.09	1.95	7.18	7.63	1.35
RHU input	2.54	1.95	1.95	2.54	1.35	1.35
Solar loading	1.60	2.14	0.00	4.6-1	6.28	0.00
Temperature (°C)						
Mounting plate	26	36	36	26	43	43
RHU holder	91	101	78	110	146	74
Actuator housing	27	37	36	29	45	43
Mounting base	29	38	37	30	47	44
Thermal shield	52	52	31	89	114	37

Table 2. Thruster Cluster Steady-State Temperatures.

Item	At Perihelion (.61 AU)			At Saturn (10 AU)		
	Non-firing		Firing	Non-firing		Firing
Housing						
Calculated	30	74	95	26	32	45
Requirement, deg C	20/50	20/50	20/50	20/50	20/50	20/50
Conditions						
Thruster firing	no	no	yes	no	no	yes
S/C attitude, deg	0	180	180	0	0	0
PM temperature, deg C	15	30	30	10	30	30
No. of RHUs	10	10	10	10	10	10
VRHU input, watts	7.2	2.0	2.0	7.0	5.7	2.4
Solar loading	no	yes	yes	no	no	no